The Some Good and Mostly Bad about Maximum Sustainable Yield as a Management Target

An American historian, Dr Carmel Finley, has described in detail how Maximum Sustainable Yield (MSY) was used, during the post-World War II negotiation of a US-Japan Peace Treaty, as a quasi-legal, pseudo-scientific concept to force Japanese fishermen to ‘abstain’ from fishing for halibut and salmon in waters adjacent to the coasts of North America, (while not restricting US tuna fishing close to South and Central America). It was said that the fish resources in that region were ‘fully utilised’, under joint governmental management, of Canadian and US fishing operations. The claim was based mainly on studies by North American scientists, particularly Milner ‘Benny’ Schaefer, who applied a logistic model to the yellowfin tuna of the Eastern Pacific and thereby launched what we now know as ‘Surplus Production’ theory. This followed in the footsteps of the Norwegian scientists Johan Hjort, Per Ottestad and Gunnar Jahn who published in 1933 their classic study of whaling. Their paper concluded:

“It is clear that a stock of whales cannot replace more than a certain number of individuals, and a wisely conducted whaling industry must act accordingly if the stock is to escape the fate of the stocks off Iceland or the coast of Spain and Portugal. There is, however, a definite level to which a stock can be reduced, while preserving the maximum capacity of regeneration and at the same time securing an optimum catch.”

Hydort et al drew a symmetrical curve of steady yield against the number of animals, but did not attribute it to P. F. Verhulst’s classic 1838 study that launched ‘the logistic curve’ of numerical population growth. Schaefer’s unwarranted shift to consideration only of gross population size by weight (biomass) set us off, I think, down a seriously mistaken path of fishing theory and management. A few years after Hjort et al M. Graham used the ‘sigmoid curve’ as a model for describing what was subsequently labeled ‘growth overfishing’ by David Cushing, but this involved taking account only of growth in body size and the natural and fishing mortality rates.

The US delegation tried, but failed, to get Schaefer-style MSY and the ‘Abstention Principle’ acknowledged as universal fisheries management objectives at a UN Technical Conference on the Law of the Sea in Rome, held in 1955 at FAO HQ. A vigorous but polite debate there between my mentor, Michael Graham, and Schaefer – on the UK and US delegations respectively - revealed a disagreement in principle between seeking a physical ‘ideal’ (the
latter) and ‘moving in the right direction’ (the former). The following legal-
diplomatic UN conference, in Geneva 1958 rejected the abstention ‘principle’
but accepted a qualified MSY-type objective. The Fisheries Convention signed
there was never effective, however, mainly because of the failure of the
Geneva Conference to agree on the breadth of the Territorial Sea. Eventually a
conditional-MSY objective was written into the well-known UN Law of the
Sea Convention of 1982 that came into effect in 1994, for nearly all states but
not the USA. 6

It having been decided at the beginning of the Third Millennium to revise the
Common Fisheries Policy (CFP) of the European Union, the Commission of the
Union put forward a proposal regarding the adoption of an MSY objective as
the basis for the revised policy. At the time I supported that move, mainly on
the grounds that in providing for recovery of over-fished and depleted stocks,
it was better than the then current policy, essentially of merely seeking
stability through a currently sustainable catch, or perhaps somewhat less than
that if some recovery was desired. However, the MSY principle applied
carelessly has its downside. I recalled when, in 1974-75, the International
Whaling Commission (IWC) adopted a numerical MSY objective for all
whaling - the Japanese position was that this meant that all ‘under-fished’
species and stocks must be reduced to MSY levels, otherwise we were
‘wasting’ a God-given resource. I guess the God was Janus, the two-faced one.

In 2011 the Commission published two Proposals for a Regulation on the
CFP:
1. The regulation should aim at securing the growth of all stocks to levels
above those that can produce the MSY as fast as possible and by 2015,
where biologically possible.
2. The resulting economic and social hardships must be cushioned
financially through the European Maritime and Fisheries Fund.

Such references to ‘level’ are commonly intended to refer to biomass but
biomass of what is rarely specified. In fisheries discourse it practically never
means ‘of the entire population’, which would includes the total weights of
larvae. ‘Stock’ is usually assumed to mean ‘recruited animals’, but what we
regard as recruitment is partially determined by biological events (shift of
habitat, metamorphosis in the case of e.g. the flat-fishes) and partially
whether the human predator regards the animals collectively as a potential
exploitable resource. Sometimes biomass seems to be taken to apply to the
exploited segment of the recruited stock, which might be all those fish above a
size/age of first liability to capture by trawls or possibly seines, but in the
case of gill-net and hook-and-line fisheries to exclude those above the
size/age of non-liability to capture. Yet another possibility, perhaps the most
relevant to efforts to manage in order to ensure unintended depletion of the
resource does not occur, is spawning stock, or mature stock, the segment of
the population comprised of sexually mature animals, which is assumed to be
proportional to the total fecundity or reproductive rate of the population. On
one side stand such alternative definitions, on the other the methods of
estimating biomass or, more usually, an index of it, by acoustic surveys,
experimental fishing, from catch and fishing effort data or by other means.
These estimates often do not coincide exactly with any of the definitions.
I was invited by the Green/European Free Alliance in Parliament to advise on how far above MSY levels it would be appropriate to aim. (My advice is in the public domain and available as a pdf file.) It was nice to do the calculations on my lap-top rather than with the hand-cranked calculator and slide-rule Ray Beverton and I used in the 1940s. I interpreted that as: ‘how far below the value of the fishing mortality rate ($F$) that would generate MSY should the fishing effort be reduced?’ I spent most of the next two years (mid-2010-2012) looking at that question, and I did so mainly by examining age-structured population models based on the equations for steady-state yield-per-recruit with constant growth and natural mortality parameters as a function of the ratio of $F$ to the natural mortality in the exploited phase, $M (m=F/M)$, of the ratio of $F$ to the growth coefficient $K$ in the Von Bertalamffy equation describing fish growth in weight ($j=M/K$), and the size-selectivity of fishing, defined by the lower end of the selective range, by fish weight, $w_c=W_c/W_{inf}$. After that I looked at the consequences of the recruitment, $R$, being dependent on the size and fecundity of the sexually mature phase of the stock. This can most easily be modeled as the apparently one but really two-parameter equation proposed by Ray Beverton and I in 1957, combined with the yield-per-recruit to provide what we called a self-regenerating system; the single parameter I call $r_0$, the ratio of the average annual number of recruits to the unexploited (‘virgin’) stock to the theoretical asymptotic number where the fecundity and/or biomass of spawners were infinite. Throughout this exercise it seemed to me important to simplify and generalize as far as possible since the Commission was seeking to define a general policy. For teleost fish $r_0$ is likely to be close to unity, for skates and rays substantially less than that, and for cetaceans much less.

At this point it is worth considering why one would wish to deviate from MSY. There are several reasons but the two most common are: as a precautionary measure, and to lighten the fisheries-footprint on the ecosystem as a whole, including incidental destruction of non-target species. But there seemed to me to be a third and much stronger reason: to ensure profitability, because without that there would eventually be no fishing, except perhaps with continued subsidies. I recalled the Great Law of Fishing enunciated by Michael Graham in his classic book, *The Fish gate*, published in 1943 and quoted at the 1955 conference:

“Fisheries that are unlimited become inefficient and unprofitable.”

It seems to be generally assumed that sustainable exploitation will usually be profitable, and that exploitation at MSY level will always be so, but there is no empirical or theoretical basis for that hope. I have come to the contrary belief: that MSY-exploitation will commonly not be economically profitable, will certainly be economically inefficient and cannot ever be economically or socially optimal. I put this conclusion as a possible question:

*Is aiming for MSY a recipe for eventual bankruptcy?*

Further, a sort of crude economic optimum – the maximum difference between the market value of a sustainable catch and the cost of taking it – is certain to come from a fishing effort substantially less than that required to
secure MSY. I am not suggesting that would be a social or economic optimal target for managing fishing but it would surely be nice to know roughly where it is.

With respect to targets and optimality the experience of the IWC is worth noting here. In developing a process for revising its management Procedure it noted three objectives; obtaining a high continuing catch over a defined finite period; having negligible risk of inadvertently depleting any stock to a dangerously low level; and avoiding if possible the need for substantial changes in catch limits from one year to the next. These are in conflict, interactive, and cannot all be simultaneously optimized (maximized or minimized as the case may be). A kind of weighted average among them was considered but abandoned for want of a methodology for objectively determining appropriate weighting factors. The only practicable solution turned out to be to get agreement on priorities among the various objectives. Fisheries managers have something to learn from this.\textsuperscript{12}

So, where is MSY? First, it is well understood that $\text{MSY}$, strictly speaking, comes from catching all the residual members of every cohort (year class) as soon as they reach the age and size at which the total weight of the cohort attains a maximum, that is just before the cohort weight declines as a result of the specific natural mortality rate overtaking the specific growth rate.\textsuperscript{13} But that is impossible except perhaps in a few special cases such as migrating salmon. So we opt for exerting a finite fishing mortality and a selectivity less than the critical value needed for $\text{MSY}$. For each chosen selectivity we generate a curve of yield-per-recruit against $j$. For low selectivities these curves have maxima, which I call $\text{local m}\text{sy}$ or just $\text{msy}$ (lower case); at higher selectivities they are asymptotic. So, for every stock, with each dynamic parameter $m$ value, there is an infinite number of local $\text{msys}$. It is convenient, for purposes of comparison and generalization, to express these as ratios to the MSY for that value of $m$, and the local selectivity parameter as a ratio of the selectivity for $\text{MSY}$, expressed as always as fish weights. All the sustainable catch values can be expressed as per the product of the recruitment, $R$, and the asymptotic body weight, $W_{\text{inf}}$.

The yield-per-recruit curves that have peaks - that is, mostly, the ones for $w_c$ equal to or less than 0.3 - are rather flat-topped, more so than any of the corresponding curves that commonly arise in surplus production calculations, which usually assume a parabolic or simple power-function shape. This means that a ‘sacrifice’ of catch by taking somewhat less than $\text{msy}$ will be ‘rewarded’ by being available with a substantially lower fishing effort and hence a higher catch rate (catch-per-unit-effort), hence potentially more profitable. The threshold selectivity value 0.3 is significant because it is approximately the weight of fishes when they become mature, being also the point of inflexion of the Von Bertalanffy curve for growth in body weight. And the higher the selectivity value the higher is the fishing effort required to obtain the local $\text{msy}$.

From the same model we can easily calculate the biomass of the exploited (selected) stock as a fraction of the stock prior to exploitation, an index of the degree (%) of reduction of catch-per-unit-effort (catch rate, hence profitability) by fishing. This leads to an interesting finding. Look at the last column of the
Table below. It shows the percentage decline in catch rates resulting when the initial exploited stock abundance is reduced by fishing down to $msy$ level – depending on the selectivity and varying rather little with the value of $m=F/M$ - the sustainable catch rate would be between about 10 and 20% of what it would have been at the initiation of the fishery. This is, of course, a substantially greater depletion than is commonly assumed when surplus production and similar models are used for stock assessments. The depletion expected when seeking maximum economic sustainable yield would be in the region of half of this, that is to between about 30 and 50%.

In this Table, by the way, the range of $m$–values is wider than has been found in field studies; the dynamics of a population of fin whales (apart from the consequences of density-dependent reproduction) turn out to be about the same as those of haddock. I regard a baleen whale as a very obese herring!

For selectivities 0.3 and less the percentage depletion of the exploited stock segment is the same as that of the mature stock segment. This makes it easy to calculate the corresponding self-generating model.

$$msy, jmsy, depletion (cpue)$$

(j is the ratio $F/M$)

<table>
<thead>
<tr>
<th>$m=M/K$</th>
<th>$w_c$</th>
<th>$msy/R.W$</th>
<th>$msy/MSY$ %</th>
<th>$jmsy$</th>
<th>$(msy/j) / (sy/j_0)$ %</th>
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<tr>
<td>0.25</td>
<td>0.4</td>
<td>0.37</td>
<td>88</td>
<td>4.3</td>
<td>14</td>
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<tr>
<td></td>
<td>0.3</td>
<td>0.34</td>
<td>83</td>
<td>3.3</td>
<td>17</td>
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<td>0.33</td>
<td>80</td>
<td>2.8</td>
<td>18</td>
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<tr>
<td></td>
<td>0.1</td>
<td>0.29</td>
<td>71</td>
<td>2.1</td>
<td>22</td>
</tr>
<tr>
<td>0.5</td>
<td>0.4</td>
<td>0.22</td>
<td>94</td>
<td>5.2</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.21</td>
<td>89</td>
<td>3.4</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>0.18</td>
<td>82</td>
<td>2.4</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.17</td>
<td>73</td>
<td>1.7</td>
<td>23</td>
</tr>
<tr>
<td>1.0</td>
<td>0.4</td>
<td>0.11</td>
<td>100</td>
<td>infinite</td>
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<tr>
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<td>0.10</td>
<td>97</td>
<td>6.3</td>
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</table>
It turns out that the location of *msys* with respect to the fishing effort (F/M) vary rather little with density dependent recruitment; the fishing mortality rate for *msy* is always somewhat less than that for constant average recruitment. The quantity *msy* itself is, however immensely variable, highly dependent on the precise value of *r_0*. This unpredictability, together with the common natural fluctuations in recruitment, led me to the conclusion that the setting of Total Allowable Catches (TACs) is a very inefficient, even hazardous, way of regulating fisheries to meet an MSY-related policy objective. The hazard is enhanced by the fact that, in a stock with many co-existent cohorts, a high fishing mortality rate (relative to a low natural mortality rate), as called for by an *msy* objective, the size and productivity of the stock are strongly conditioned by one or a few of the youngest cohorts.

I have not yet mentioned some major issues. One is the transient forms of the yield equations, needed to assess the problems of moving responsibly from one population state to another – steady – one; that would take longer than we have here. The other arises from the fact that, unlike diamonds, sustainable states are not ‘forever’. That is rarely understood by those who talk so much about the ‘sustainability’ of this or that as if it will be eternal or nothing. For scientific analysis they – steady states - must be given fixed terms, possibly arbitrarily but preferably related at least to the life-span of the species in question, the durability of human systems for management, and the power of computing systems for conducting the many necessary simulations of fishery histories and prospective management systems. The Scientific Committee of the IWC, which possibly has more experience of dealing with this problem than most, found that in fact the choice of time-frame can make important differences to conclusions and management procedures. (I use that term here in the sense of, for example, medical procedures which specify exactly how and in which order steps in the execution of an algorithm must be taken)

Other important matters are, of course, the estimation of essential parameters, and stochastic processes.

I would like to close with two more of Michael Graham’s aphorisms. The first, from the 1955 Rome conference:

"The trail of fishery science is strewn with opinions of those who, while partly right, were wholly wrong."

The second, in his address to the United Nations Scientific Conference on the Conservation and Utilisation of Resources (UNSCCUR), held at Lake Success, New York, in 1949, the first, post-war, UN conference devoted to this subject:

"The World does not stand still while scientists put their minds in order."

Graham’s *Bons Mots* may be as valid today as they were then.

I thank Dr Michael Earle for his helpful critical reading of earlier drafts of this presentation. Thank you.


3 Verhulst was a Belgian mathematician who put forward theorems of restraints on human population growth that countered the theory of exponential growth leading to catastrophe propounded by the British Rev. Thomas Malthus, who published six editions of his ‘Essay on the Principle of Population’ between 1798 and 1826. This pre-Darwinian controversy was of profound importance to the new proto-capitalist society needing to believe in ‘Progress’.

4 There are many problems on that path, particularly arising from the absence of empirical evidence regarding its basic assumptions about the forms of density-dependence, but the most damaging of which is that population productivity is a simple function of population biomass. Two populations of a species, having the same biomass, can differ immensely in their biological productivities. The surplus yield model under-values and impedes consideration of the importance of fishing selectivity in the consideration of sustainable fishing scenarios.


6 "---measures shall -- be designed to maintain or restore populations of harvested species at levels which can produce the maximum sustainable
yield, as qualified by relevant environmental and economic factors, including the economic needs of coastal fishing communities, and taking into account fishing patterns, the interdependence of stocks and any generally recommended international minimum standards.

7 "Reform of the EU Common Fisheries Policy (CFP): How to Achieve Sustainable and Profitable Fishing". References to many of the ideas expressed here are given in my "Forward to the 4th edition, 3rd reprint (2003) of Beverton and Holt 1957 "On the Dynamics of Exploited Fish Populations!"


9 See Beverton, R. J. H., and Holt, S. J. (1966) Manual of Methods for Fish Stock Assessment. Part II Tables of Yield Functions. FAO Fish. Tech. Pap. 39 Rev.1. 67pp. In English, French and Spanish. In these tables the selectivity was given as a length, c, relative to the theoretical asymptotic length. Here I use for the index of selectivity a fish size at first liability to capture as a fraction of the asymptotic weight, \( w_c = c^3 \).

10 The two constants in the original version of this expression are in fact only scalars. Now I would set both the spawners and the recruits in the unexploited stock at unity.


13 The relevant expressions are:

\[
\text{MSY/R.W}_{\text{inf}} = \left( \frac{m}{3+m} \right)^m \times \left( \frac{3}{3+m} \right)^3
\]

Critical weight: \( w_{\text{MSY}} = \left( \frac{3}{3+m} \right)^3 \)

Age at critical weight: \( a_{\text{cri}} = \ln(\frac{3+m}{m})/K \)

Basic Von Bertalanffy expression for body weight relative to asymptotic weight;

\[
w = (1 - e^{-ak})^3
\]

14 In his perceptive little book "The oceans are Emptying: Fish Wars and Sustainability" (1995, 176pp, Black Rose Books) Raymond A. Rogers wrote that the popular but entirely arbitrary reference point for management -- \( F_{0.1} \) -- lies between \( F_{\text{msy}} \) and \( F_{\text{mesy}} \). But it is not self-evident that \( F_{0.1} \) will always be higher than \( F_{\text{mesy}} \).

15 The expression from the B&H S-R relationship, for the reduction of recruitment arising from the reduction of the virgin spawning stock by fishing is:
\[ d_r = \frac{r}{r_0} = \frac{1}{(r_0 + (1-r_0)/s)} \]

where \( s \) is a number between unity and zero

If \( s \) is put equal to 0.2 in this expression \( d \) becomes what has been called the ‘steepness’, \( h \), of the stock-recruitment relationship.

It would be reasonable to ask what difference to the self-regenerating equations might result from use of a stock-recruitment relationship other than the inverse hyperbola of Beverton & Holt. An obvious alternative might be a simple power function giving a convex (from above) curve with \( r = 0 \) when \( s = 0 \), \( r = 1 \) when \( s \) = infinity, and scaled to \( r = r_0 \) when \( s = 1 \), e.g:

\[ r = 1 - a^{-s} \quad \text{so} \quad a = 1/(1-r_0) \quad \text{and} \quad r = 1 - 1/(1 - r_0)^s \]

[This happens to be exactly the form of a relationship between a linear dimension such as total body length of a fish and its age, discovered by E. Ford in 1933 for North Sea herring, and rediscovered by L. Walford in 1949 and applied to a wide range of fish species; it is the core of Von Bertalanffy’s general expression for growth.]

Application of this and similar alternative stock-recruitment functions can lead to slightly different predictions of recruitment change with increased fishing effort, but virtually no significant difference to the predicted shift of the msy towards a lower \( j \)-value.

A more flexible expression with an additional parameter to the B&H expression as proposed by Shepherd (1982), could give significantly different results quantitatively, especially for very greatly depleted stock situations, where depensation (the ‘Allee effect’) may come into play. That should be investigated.